THE VALUE OF ISO3382 FOR RESEARCH AND DESIGN

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1 INTRODUCTION

ISO3382 appeared in 1997 titled "Measurement of the reverberation time of rooms with reference to other acoustic parameters". The previous version from 1975 concerned itself exclusively with reverberation time. Now the 1997 version is being revised into a Part 1 (the 1997 standard intended principally for performance spaces) and Part 2 for reverberation time measurements in ordinary rooms. The intention is that the accuracy of measurement in ordinary rooms can be less than in auditoria (mainly allowing for fewer source and receiver positions).

The following measures are defined in the 1997 standard:

reverberation time - main body of standard

sound strength (G) - Annex A

early decay time (EDT) - Annex A

balance between early and late arriving energy (C_{80} and others) - Annex A

early lateral energy measures (LF and LFC) - Annex A

inter-aural cross correlation function (IACF) - Annex B

This paper will restrict itself to concert hall measurements and be concerned principally with the newer measures from Annex A.

2 THE ORIGINS OF OBJECTIVE MEASURES

One quibble about this standard is that the origins of the various measures are not given. This point is important because the circumstances relating to the proposal of a measure may be significant for its relevance. All the new measures have been proposed following subjective testing, either in the laboratory or in real concert halls. There is evidence that each of the measures is significant in the real listening situation, but there is the risk for instance that laboratory testing has been done for example with a restricted number of reflections relative to what is found in real halls.

Much of the progress in concert hall acoustics has come from experiments made in anechoic chambers using simulation systems. A simulation system uses an anechoic recording that is fed to an array of loudspeakers arranged roughly on a hemispherical surface around the head of the listener. Delays (originally derived from tape delay machines, but now produced electronically) are used to simulate reflections, while reverberation is produced either by using reverberation chambers, reverberation plates or now electronic reverberation. Subjective testing using a simulation system was pioneered at the University of Göttingen under the direction of Prof. Erwin Meyer. One of their first publications by Haas in 1951 [1] has been the key to the design of public address systems ever since. Much of the Göttingen work during the 1950s and early '60s was summarised in English in reference [2].

The key measure to emerge from Göttingen was the 50ms early energy fraction, proposed by Thiele [3] in 1953 as a measure of clarity or distinctness, *Deutlichkeit* in German. This measure is often referred to as D_{50}, whereas C_{50} is the logarithmic ratio of early-to-late energy uniquely related to D_{50}. D_{50} has been shown to correspond well with speech intelligibility and is still used for this purpose.

2.1 Clarity Index, C_{80}

A longer time period than 50ms for the early sound has been found appropriate for clarity with music; 80ms is generally used. Hence the early-to-late sound index or Clarity Index, C_{80}, first explicitly proposed by Reichardt *et al* [4]. Measures such as C_{80} can be criticised for having a sharp temporal cut-of; reflections arriving around 80ms will either contribute to the early or late part depending on their precise delay. The centre time, proposed Cremer [5, p.343] avoids this problem by having time as the unit for the measure. The centre time is the centre of gravity along the time axis of the squared impulse response. It is however so highly correlated with early decay time that it is not often used as an independent measure.

2.2 Initial-Time-Delay-Gap

Beranek's survey [6] of 54 of the world's concert halls and opera houses published in 1962 produced an apparently major new result. From comparison of subjective and objective results, he proposed that the initial-time-delay-gap (the delay of the first reflection in the main body of the Stalls) was the most important determinant of acoustic quality. In the best-liked concert halls the delay gap was 21ms or less. This proposal has however been questioned for several reasons.

A major criticism relates to the first hall designed according to this measure, which was much criticised for its acoustics and eventually demolished; Philharmonic Hall, New York opened in 1962 but the auditorium was completely replaced in 1976. One suggestion for the anomaly is that in traditional halls the first reflection tends to arrive from the side, whereas in Philharmonic Hall a suspended reflector array was introduced to provide a strong early reflection from overhead. Beranek considered the initial-time-delay-gap to be a measure of perceived acoustic intimacy. If one looks at the situation within a concert hall, the delay gap decreases as one moves away from the source. Subjective surveys however show intimacy decreasing towards the rear of halls, the opposite of what one would expect from the initial-time-delay-gap. This is therefore a second major criticism of the measure. The initial-time-delay-gap does not appear in the standard, though it has its champions, among them Ando [7].

2.3 Early Decay Time, EDT

Atal, Schroeder and Sessler [8] investigated assessment of the sense of reverberation by subjects comparing non-linear and linear decays. They found that either the decay rate over the first 160ms or over the first 15dB of the decay proved to be the best correlates of perceived reverberation. Jordan [9] subsequently proposed in 1970 that the decay rate over the first 10dB should be measured, naming it the early decay time. The EDT is thus a measure of 'reverberance', superseding reverberation time.

There are however two situations in which reverberation is perceived. Running reverberation heard during continuous music is usually considered the more important and it is this that is assessed by the EDT. At the end of a section of music, terminal reverberation can be heard; the full decay as measured by the reverberation time can be heard. Most consultants consider terminal reverberation to be of minor importance.

Does reverberation time still have a place for auditorium design? The answer to this is a definite yes, as a reference figure. The reverberation time is generally the same throughout the auditorium and can usually be calculated with reasonable accuracy using the Sabine formula. The early decay time varies throughout the auditorium and for instance takes low values under balcony overhangs. The ratio of the mean EDT to reverberation time (RT) is a useful parameter which relates to the 'directedness' of an auditorium design [10]. In a hall where surfaces direct sound onto audience seating, the mean EDT/RT ratio can take values down to 0.82.

2.4 Spatial Measures

The issue of objective measures for spatial effects heard by listeners has been complicated by the presence of two competing measures: the early lateral fraction, LF, and cross-correlation measures. Both these measures are defined in ISO3382. A substantial literature exists relating to these two different objective approaches. The situation has become further complicated recently with the suggestion firstly by Morimoto and Maekawa [11] in 1989 that there are two important spatial effects; source broadening due to early lateral reflections and listener envelopment linked to the later sound. This subdivision is now widely accepted.

Most research relating to spatial hearing in concert halls in the period 1967-1995 was concerned with what is now called source broadening, but was mainly at the time referred to as spatial impression or spaciousness [12]. This work followed the suggestion by Marshall [13] concerning the importance of early lateral fractions for music listening. The objective measure, the early lateral fraction, was proposed as a practical measure that arose from subjective tests by Barron and Marshall [14]. However it is clear that source broadening is caused by differences between the signals at the two ears, which points logically to a cross-correlation measure, first employed by Keet [15]. Interaural cross-correlation function (IACF) measures have been championed for instance by Ando [7].

Blauert [16] and others have proposed models of our hearing system to extract source broadening. These are based on many frequency bands being processed simultaneously in parallel with a running cross-correlation process taking place. This is considerably more complex than the simple measure proposed in Annex B of ISO3382, in which octave filtered analysis is proposed.

There is considerable evidence that low frequencies make a substantial contribution to the sense of source broadening [17. 14. 18, 19]. There is however a problem with IACF measures at low frequencies since they hardly vary. This difficulty does not arise with the lateral fraction [20]. Okano, Beranek and Hidaka [21] have proposed combining an IACF measure at mid-frequencies with a measure of low frequency sound strength to deal with this complication. To this author, this seems an awkward compromise.

There is general agreement that the degree of perceived source broadening is also a function of sound level, as first proposed by Keet [15]. A combined measure for the lateral fraction and sound level has been proposed by Marshall and Barron [12].

As an objective measure for listener envelopment, Bradley and Soulodre [22, 23] have suggested the late lateral sound level (GLL). This proposal arrived too late to be incorporated in ISO3382. From analysis of measured values for GLL, Barron [24] found that by far the major determinant of GLL was the total acoustic absorption in auditoria.

2.5 Sound Strength, G

Interestingly Sabine mentions a loud sound as being one of three necessary conditions for good hearing [25]. Whereas the other new objective measures arose from simulation experiments in acoustic laboratories, the importance of sound strength was shown from a study by Lehmann and Wilkens in 1980 [26] that involved subjects assessing recordings made at orchestral rehearsals in actual concert halls. The sound strength is simply the total sound level measured at seat positions, normalised to the direct sound level at 10m from the source. Prior to then, the variations in level between concert halls was thought to be too small to be perceived. A recent publication by Okano [27] suggests that the difference limen for sound level is only 0.25dB, a value which may appear too small for some. Measurements in British concert halls [28, p.189] showed a range of 9dB between the quietest and loudest seat position in halls with over 1500 seats.

As well as strength being significant for subjective loudness, it also appears to be the major determinant of subjective intimacy [28, p.188]. This objective measure for intimacy is thus an alternative to Beranek's initial-time-delay gap (section 2.2).

3 SUBJECTIVE CRITERIA

There are many verbal expressions used for subjective response to live music performance. It is certain that further subtleties remain to be resolved. At least eight subjective qualities are currently mentioned fairly regularly, as listed in Table 1 together with recommended objective measures. Listeners with some experience of completing questionnaires can usually comment on each of these subjective qualities. There is substantial evidence however that listeners vary in their preferences, so that they select different criteria when making an overall judgement. Subjective studies to date conclude that listeners subdivide into at least three groups: those that prefer either clarity or reverberance or intimacy above other concerns [28, p.188]. It is clear that a simplistic interpretation of the significance of the measures found in ISO3382 is unwise.

Table 1. Subjective qualities in concert halls and their possible objective correlates

Subjective quality	Objective measure
Clarity	Clarity Index (C_{80})
Reverberance	Early decay time
Intimacy	Sound strength
Source broadening	Early lateral fraction and strength
Listener envelopment	Late lateral level
Loudness	Sound strength and source-receiver distance
Brilliance	?
Warmth	Bass level balance?

A mystery at present in concert hall acoustics concerns the subjective effects of substantial diffusing surfaces on the walls and ceiling of halls. There is some evidence that listeners prefer diffuse conditions [29] but it is not conclusive. Not only can the state of diffusion not be quantified but no suggestions have been offered for how we perceive diffusion.

4 OBJECTIVE MEASUREMENT PROCEDURE

In several respects the usual measurement conditions in halls differ from the performance situation. A major difference is that of occupancy, both in the audience seating and on the stage. Fortunately most concert halls have well upholstered seating which, though never as absorbent as occupied seating, is almost as absorbent. It is likely that in most concert halls, the correction of objective measures for the change of reverberation time is sufficiently accurate. Corrections should be applied to all measures except the spatial ones [28, p.418-9]. Hidaka, Nishihara and Beranek [30] have also investigated correction for occupancy.

When one goes to make a measurement in a hall, one can either find the stage empty or occupied with chairs and music stands. Of these the latter is definitely to be preferred. Though unoccupied chairs on stage are less of an obstruction to sound compared with occupied ones, chairs and stands will partly obscure stage floor reflections, which may be a significant component of the early impulse response. The presence of chairs on stage also influences the measured sound strength and may easily reduce the sound level by a decibel or more. The ISO standard rightly specifies that the stage conditions should be carefully recorded.

The possible influence of stage floor reflections should also be taken into account when choosing sound source locations. For my own measurements, I have tended to use a single source position on the hall centre line 3m from the stage front. This location was chosen to minimise the chance of stage floor reflections occurring. With a full orchestra on stage, these reflections will be obscured. Using just a single source position can of course be criticised since conditions are likely to vary with source position on the platform. However this seems a lesser risk than the inclusion of floor reflections for some source positions and not others. In other words, in the absence of chairs on stage, a single forward source position seems the best compromise, when one wants to measure conditions appropriate to an orchestra performing on stage.

A much less manageable difficulty with objective measurements concerns the source. An orchestra occupies around $200m^2$ of stage with instruments which each have a complex directivity, which also changes depending on the note being played. The standard measurement technique is to use a single omni-directional source, usually a dodecahedron loudspeaker. To appreciate the artificiality of a single source, one needs to listen to anechoically recorded music played through an omni-directional source on a concert hall stage; it is a lifeless listening experience. No research into the significance of this issue has been done, to my knowledge.

5 MEASUREMENT FREQUENCIES AND AVERAGING OF RESULTS

The ISO standard avoids being precise about the appropriate frequencies for measurement nor does the standard say how results should be averaged to establish the expected clarity, or whatever, in a concert hall. It is recommended that measurements be taken in the six octave bands from 125 - 4000Hz. The standard suggests quoting results by averaging over pairs of octaves to give low, mid- and high frequency values. Bradley [34] uses this approach for timbre-related parameters.

There are however two complications that occur at the 4000Hz octave. Firstly the reverberation time etc. are sensitive to air absorption, determined by temperature and relative humidity. The main part of the standard says that temperature and humidity should be measured. The second difficulty at 4000Hz is that the standard dodecahedron loudspeaker (with a diameter of the order of 400mm) becomes directional at this frequency. One can compensate for this difficulty by making several measurements with different orientations of the loudspeaker, but this is time-consuming. Behler and Müller [35] have solved this problem by using a separate 100mm diameter dodecahedron for high frequency measurements.

Barron [31, 32, 33] has tended to measure over five octaves 125 - 2000Hz and divide results into a bass region, 125 - 250Hz, and a mid-frequency region, 500 - 2000Hz. The major differences between the bass and mid-frequency are different amounts and type of absorption (usually panel vs. porous absorption) and that the bass frequencies are affected by the seat-dip effect [28, p.19-21], for which the frequency of maximum absorption lies within the two octaves 125 and 250Hz. Since individual octave measurements are influenced by interference, either constructive or destructive, it is preferable to use averages of several octaves where appropriate.

This last point, about averaging octave results to reduce interference effects, does not apply in the case of most computer simulation programmes, since they ignore the wave nature of sound. Simulation programmes generally ignore wave effects so that, to gain a result equivalent say to the average of 500 - 2000Hz, a computation only at 1000Hz may be suitable, as long as absorption coefficients etc. for 1000Hz are the average of those for the frequency range in question.

The standard specifies that for halls with more than 2000 seats at least 10 seat positions should be measured. With five or more measures at five or six octaves, a lot of data is generated. To make sense of this plethora of numbers, some averaging is appropriate. How this is done is likely to be a personal decision; some recommended frequency ranges for the different measures are included in Table 2 [36]. For perceived clarity, there is little evidence that the bass contributes to this subjective quality, hence the suggested mid-frequency range. In the case of the early lateral fraction, the low frequencies are known to be particularly significant whereas high frequencies are less so.

Table 2. Possible recommended frequency ranges for octave band measurements in concert halls.

Measure	Frequency range (Hz)
Reverberation time	125-4000
Early decay time	125-2000
Clarity Index (C_{80})	500-2000
Early lateral fraction, LF	125-1000
Sound strength, G	125-2000

A further diagnostic analysis involves deriving the mid-frequency early and late sound levels from the early-to-late index and sound strength. The early and late levels can be plotted against source-receiver distance and compared with predicted values according to revised theory [31]. Plots of the mid-frequency total level (early + late) against source-receiver distance have been made for British concert halls [28].

Regarding averaging over position, overhung seats should be treated separately for EDT, C_{80} and strength, since values under overhangs are different for these measures [33]. Apart from treating overhung seats separately, serious deviations from expectations should be investigated. It is sometimes worthwhile comparing values for different seating areas, such as the stalls and circle. The measures other than reverberation time and EDT vary however with distance from the source; again comparison with revised theory can help for C_{80} and strength. LF tends to be smaller close to the source, due to the dominance of the direct sound [20].

An extreme form of data reduction is to average over all measured positions in a concert hall, as is found in Beranek's extensive survey of world concert halls [37]. As an example of the difficulties this presents, Table 3 shows a comparison of mean values for two British halls. This comparison is with values averaged over frequency as well as measurement position, but other than the spectrum for reverberation time and EDT, the additional frequency data is often more confusing than helpful. St David's Hall, Cardiff, was one of the best-liked halls in a subjective survey of 11 British halls [36], whereas the Barbican Concert Hall was one of the least liked. Both halls have around 2000 seats and were measured at 11 or 12 positions.

Though one would certainly pick St David's Hall as being likely to be preferred on the basis of the longer reverberation time and EDT, the differences in the other measures are surprisingly small. Most issues apparent from subjective investigation cannot be guessed from this data, whereas consideration of objective data by position provides a much fuller picture [28].

Table 3. Comparison of mean objective data of two British concert halls. Where appropriate, values have been converted to the occupied condition.

	Frequency range (Hz)	St David's Hall, Cardiff	Barbican Concert Hall, London

Mean occupied reverberation time (s)	125-2000	1.91	1.66
Mean occupied EDT (s)	125-2000	1.96	1.74
Mean Clarity Index (dB)	500-2000	-0.6	-0.3
Mean lateral fraction	125-1000	0.17	0.12
Mean strength (dB)	500-2000	3.0	2.2

6 ACCURACY AND CALIBRATION

Two key measurement exercises have been published that looked at the reliability of different measurement systems measuring the same room [38, 39]. While these show that some measurement systems are unreliable, this is likely to be due to poor understanding of signal processing. With informed measurement systems, measurement scatter appears to be comparable to audible difference limen [38].

Naqvi and James [40] have also raised the issue of calibration. The standard could certainly be more prescriptive about calibration for measurement of strength.

7 USE OF ISO3382

7.1 ISO3382 and Research

Research requires freedom, freedom of ideas, freedom of direction. Academic research requires academic freedom, an issue which arises even on the political level from time to time. Standards on the other hand can be seen as restricting liberty. Yet for researchers, standards do not provide rules that have to be followed. Standards are in fact regularly revised and if they are good standards they should represent best current thinking. For research the big virtue of a standard is that it provides points of reference.

For example, if someone is studying clarity in concert halls, the fact that the standard proposes the Clarity Index (C_{80}) means that whatever else is studied, results are compared with the Clarity Index. This should allow direct comparison between different pieces of research work, a situation that has in the past often not been possible.

The basis of the new measures in the Annexes of the standard is of course subjective experiment. Virtually all subjective work relating to auditorium acoustics can be criticised for one reason or another, usually for the scope of listening conditions tested. The status of the proposals in the standard should thus been seen in this light. As mentioned already above, the standard could be more prescriptive than it is, though this would depend on agreement between key workers in the field.

7.2 ISO3382 and Design Consultancy

The existence of a standard offers to consultants the possibility to assess auditoria they have designed. Reports can be filled with numerical data, the standard can be mentioned. But this is a lamentable trend unless those who write the reports have a good understanding of what is the significance of the numbers and how they best be averaged and presented. For design purposes, objective measures become particularly important for modelling during the design phase of an auditorium.

7.2.1 Objective Measures and Modelling

Two types of modelling are now commonly used: acoustic scale modelling and computer simulation modelling. In both cases both subjective and objective testing are possible. In scale models, anechoic music is most frequently convolved with impulse responses measured in the model; with computer models the same process is termed 'auralisation'.

At first sight, subjective testing, which allows people to hear what a new design will sound like, appears more attractive. Yet the problem of assessment is difficult. All simulation systems will have some imperfections (correct source modelling is a major issue here), so that in a single assessment one does not know to what extent one's judgement is influenced by those imperfections. Comparative judgements are more promising, though the designer should have a wide range of subjective samples for comparison generated by the same simulation system.

Objective measures on the other hand can be compared both with published criteria proposed in the literature and with the reasonable volume of data in the public domain. A standard has a major role in ensuring that measurement and analysis procedures are such that direct comparisons are valid.

However in its present form, the standard is not sufficiently prescriptive for a designer without significant experience to be reliable using objective measures. Is a particularly low value of some objective parameter at a location in a concert hall cause for concern and if so what geometrical or other acoustically significant feature of the auditorium is responsible for the objective performance?

8 RELIABILITY OF OBJECTIVE MEASURES

To illustrate the reliability of the new objective measures, two concert hall examples will be reviewed; for further details about the halls, see [28]. In the Royal Concert Hall, Nottingham, subjective and objective agree well, whereas in the Barbican Concert Hall, London, the agreement is less impressive. Both halls were completed in 1982 and happen to have the same auditorium volume. Objective data was measured in 1983-4.

The Royal Concert Hall has a seat capacity of 2500 and a volume of 17,510m^3. It was subjectively judged as having high clarity but a low reverberance. For the other subjective qualities of envelopment, intimacy and loudness, the hall scored well, with an overall assessment of 'Good'. A high subjective bass balance (warmth) was noted. The sound quality was however criticised for the harsh quality of the sound.

Figure 1 shows the objective characteristics of the Royal Concert Hall. In the case of clarity and source broadening, the pediment shows the range and mean of measured values. Total sound level (or strength) is plotted according to the individual measurement positions. Measured values of objective clarity and level have been corrected from the unoccupied to the occupied reverberation time.

The occupied mid-frequency reverberation time is short at 1.7 seconds (mean of 500 - 2000Hz), as is the 'occupied' early decay time at the same frequency of 1.5 seconds (correcting for occupancy). This corresponds well with the judgement of low reverberance. Objective clarity and source broadening are both high and sound levels are all above the criterion value of 0dB. There is a long low frequency reverberation time, with a high objective bass balance in this hall which would explain the strong bass perceived here. The comment about harsh sound quality cannot be matched with any of these objective measures but can be inferred from the use a large unmodulated plane surfaces in this hall, which are oriented to supply strong early reflections.

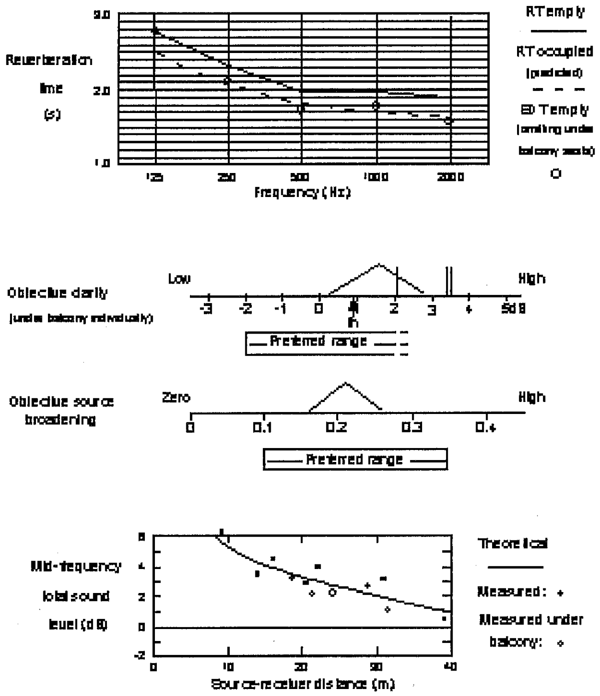

Figure 1 . Objective results, Royal Concert Hall, Nottingham

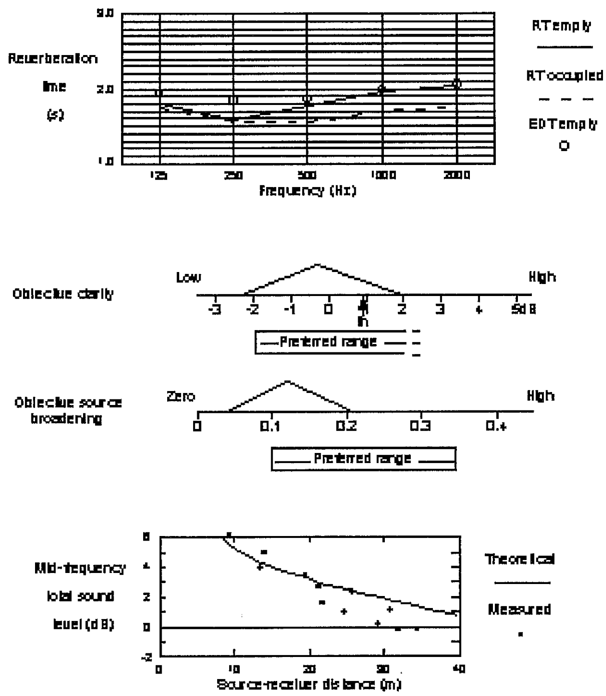

Figure 2. Objective results, Barbican Concert Hall, London

The Barbican Concert Hall has 2026 seats with a volume of 17750m^3. The clarity was judged as reasonable in this hall but on other subjective qualities of reverberance, envelopment, intimacy and loudness the judgements were low. Bass sound was weak and there were some differences in judgements between different seat positions.

Objective results for the Barbican Concert Hall are given in Figure 2. The reverberation time is clearly short in this hall and the 'occupied' EDT (500 - 2000Hz) is 1.7 seconds. Though objective clarity, source broadening and sound levels are rather low, the deviation from preferred values is not sufficient to justify the poor subjective judgements corresponding to each of these measures. There is however both a low subjective bass balance (warmth) and low objective bass balance.

These two examples illustrate that objective measures are not always wholly reliable guides to subjective quality. Hence the need for experience in their use. In the case of the Barbican Hall, there is the possibility that conditions change more markedly with an audience present, whereas occupied results here have been derived from unoccupied measurements.

9 CONCLUSIONS

In a recent review of standards dealing in particular with ISO3382, Naqvi and James [40] found that most people measuring auditoria did so "generally in accordance with the principles of ISO3382". They ascribe this partly to the uneven character of the standard, in places over-prescriptive and in others insufficiently so. Some refinements of the standard are obviously called for.

In the above, the origins and use of ISO3382 have been discussed. The point has been made that there is no substitute for a thorough understanding of the basis of the various measures and of their behaviour in actual auditoria. Not surprisingly, current acoustic consultants differ in the degree to which they use objective measures and use acoustic modelling. The alternative is to rely on precedent, limit the number of risks one is taking and hope to gain experience from each auditorium completed. Ultimately all consultants are engaged in trial and error; with objective measures the trial and error extends to their validity. From this process, the art and science of auditorium acoustics develops.

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